the $^2P_{1\frac{1}{2}}$ limit. Electrons excited to any of these states are in the *continuum* of the lower set of levels having the same quantum numbers and parity, but approaching the lower limit. The result is, the ejection of an electron, (i.e. *auto-ionization*) and the return of the atom to the lower limit $^2P_{1\frac{1}{2}}$.

Three members of the $^3P^e$ ($3dmd$) series in calcium, made famous through the work of Russell and Saunders, lie above the series limit, $4^2,S_{\frac{1}{2}}$, of the four chief series of singlets and triplets. The continuum above these four chief series corresponds to *even* S and D terms and to *odd* P and F terms. The *mean-life* of the three negative $^3P^0$ states is sufficiently great therefore to combine normally with lower *odd* terms and give respectable spectrum lines. The observed $^3S^3$ term, attributed to ($3d4d$) by Russell, in combination with other terms gives, as would be expected from a short mean-life, diffuse lines.

In strontium a negative $^3F^0$ term ($4d5p$) lies above the $5^2S_{\frac{1}{2}}$ limit and in a continuum of $^3F^0$ terms ($5s4f$). These negative $^3F^0$ ($4d6p$) terms, because they are observed at all, would be expected to have a very short *mean-life* and should therefore give rise to diffuse lines, as observed. These same $^3F^0$ terms in barium lie below the first limit $6^2S_{\frac{1}{2}}$ and give rise to sharp lines, as expected.

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On the Range of Fast Electrons and Neutrons

Recent experiments on the stopping of cosmic rays raise again the question of the energy losses of electrons and protons with velocity very close to that of light. On the one hand we have a good deal of evidence that there are, associated with the cosmic rays, rays which are certainly not gamma-radiation, and which behave in some respects like beta-rays, since they produce a large number of ions in their passage through matter. This conclusion, which was reached originally by experiments with Geiger counters in series, has been beautifully confirmed by Mott-Smith,[1] who was able to show that the cosmic rays are accompanied by particles which produce definite cloud-chamber tracks, tracks rather thinner than those of an ordinary radioactive beta-particle. These ionizing rays are, according to Rossi, at least as penetrating as the cosmic rays themselves, and perhaps more so. On the other hand the independence of cosmic-ray intensities of terrestrial latitude makes it hard to believe that the rays enter the earth's atmosphere as charged particles. We should then want to know the theoretical answer to the question: Can a gamma-ray produce secondary beta-particles more penetrating than itself?

Numerous calculations have been made of the range of particles moving with velocities not too near that of light. Thus quantum-theoretical formulae have been obtained by Gaunt and Bethe, which in essential points confirm the classical formula of Bohr. But no quantum theoretical calculations have been made for particles of very high energy; and the classical result of Bohr for this case is based on a derivation which is not quite free from objection. Now it would seem at first that no adequate calculation could here be made, since we have at present no complete theory of the interaction of particles of very high relative velocity. That such a calculation is, nevertheless, possible rests on the fact that the processes chiefly responsible for the stopping of a beta-particle involve relatively insignificant energy losses, and that the mean energy loss of a beta-particle on collision with an atom is very small. This preponderance of relatively small energy losses becomes even more marked for particles whose velocity approaches that of light, and makes it possible to calculate the range of the particles without neglecting the retardation of the forces between them and the atomic electrons. Such a calculation has in fact been made by Møller for the collision of two free electrons; we have made it for the collision of electrons and protons with electrons bound in an atom. The results are very simple. If the energy of the particle (rest mass M, and charge E) is

$$\epsilon Mc^2$$

then for *very* large ϵ the number of ions produced per cm path increases with $\ln\epsilon$, and the energy loss per cm path through a gas in which there are N electrons per cc is

$$[4\pi e^2E^2N/mc^2]\cdot \ln \epsilon. \qquad (1)$$

[1] We want here to thank Dr. Mott-Smith for telling us at a Berkeley seminar of his recent very beautiful experiments.

Here e and m are the electronic charge and rest mass. For large but not very large ϵ this formula must be modified: to $\ln\epsilon$ must be added

$$\ln mc^2/khv$$

where m is the electronic rest mass, v a mean ionization frequency for the atomic electrons, and $1.1 \leqq k \leqq 1.2$. This term is just the one found by Bethe for slow electrons, and in every case reduces the range of the particle below the value given by (2). The formula (1) gives for the range R of the particle

$$R = [mMc^4/4\pi e^2E^2N] \cdot [\epsilon/\ln \epsilon] \qquad (2)$$

This range is just twice that given by Bohr's relativistic formula. Our result gives equal ranges to electrons and protons of equal energy, and makes this range just one fourth of the mean distance, which, according to the Klein-Nishina formula, a gamma-ray of this same energy travels before its first Compton scattering.

The result (1) makes it hard to believe that the particles observed with cosmic rays are electrons or protons, since they are observed to ionize less than slower beta-particles. And if we believe in the approximate validity of the Klein-Nishina formula, then (2) shows that the particles cannot be secondary electrons. We have therefore thought it of interest to investigate the ionizing power of the neutrons, which were suggested by Pauli to salvage the theory of the nucleus. These neutrons,[2] it will be remembered, are particles of finite proper mass, carrying no charge, but having a small magnetic moment. Although the full calculations of the collision of such a neutron with an electron have not yet been completed, we have carried them far enough to see that there are characteristic differences between the ionizing power of a neutron and that of an electron, differences which rest ultimately upon the fact that the field of the neutron falls off more rapidly with distance than the Coulomb field. (The field of a neutron may, of course, be derived from its wave equation; and this has been given by Pauli.) In particular, the number of ions produced by a neutron is, for energies large compared to the electronic proper energy mc^2, sensibly independent of the velocity of the neutron, and of its mass, and does not increase, like (1), with increasing velocity. Thus even a very fast neutron would, if its magnetic moment were of the order of that of the proton, produce ion tracks perceptibly thinner than those of a beta-particle. It will be remembered that, according to Pauli, it is one of the functions of the neutron to carry off the apparently lost energy in a radioactive beta-ray disintegration. It would be of extreme interest to see whether, in such a disintegration, thin tracks, of the kind observed by Mott-Smith, could be found. If they were found, we should be certain that the neutrons not only played a part in the building of nuclei, but that they also formed the cosmic rays; if no such tracks were found, we should know that the neutrons, if they exist at all, have nothing to do with cosmic radiation.

The theory of the collision of neutrons and electrons, and the detailed calculation of the ranges of neutrons and fast electrons, will be published very shortly.

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October 9, 1931.

[2] We are much indebted to Dr. Pauli for telling us, at a theoretical seminar in Ann Arbor last summer, the elements of the theory of the neutron, its functions and its properties.

The Calculation of the Characteristic Frequency from the Coefficient of Compressibility

A number of years ago Einstein[1] derived an expression for the characteristic frequency of a monatomic solid which is as follows

$$\nu = 2.8 \times 10^7 A^{-1/3}\rho^{-1/6}\kappa^{-1/2} \qquad (1)$$

where κ is the coefficient of compressibility, A is the atomic weight and ρ is the density of the solid. This relation was derived from dimensional considerations, and the constant was evaluated by considering the effect on a given atom of its 26 immediate neighbors in a lattice which we now call the simple cubic or rock salt type. The result must be regarded as an approximation yet it is a useful one and therefore deserves further consideration. A reexamination of the derivation in the light of present knowledge reveals that several ambiguities and restrictions inherent in the original work now may be removed.

[1] Einstein, Ann. d. Physik **34,** 170 (1911); **35,** 879 (1911).